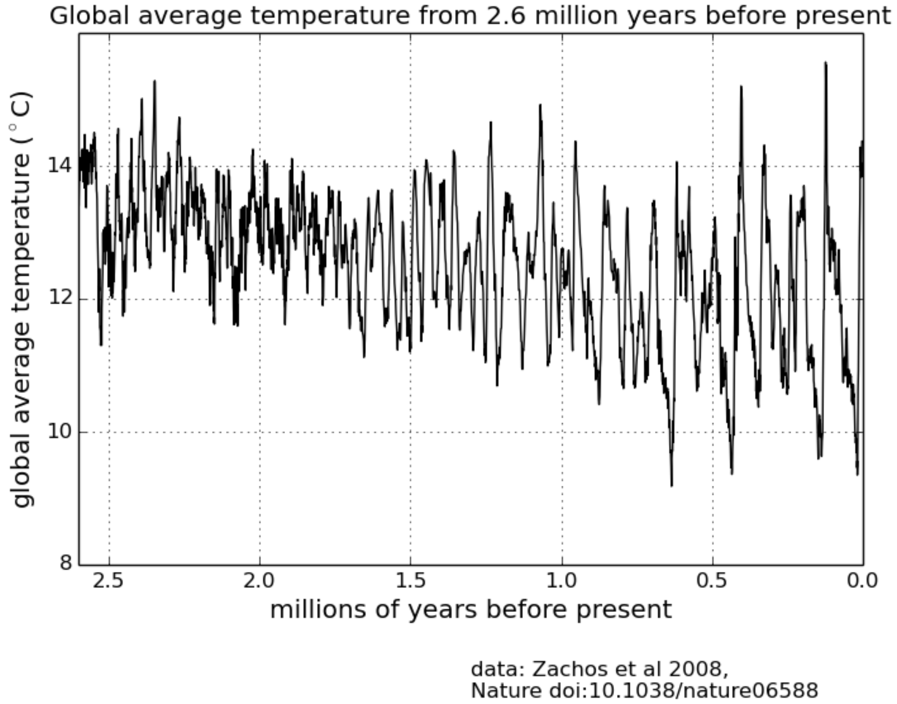
MetLink
Royal Meteorological Society

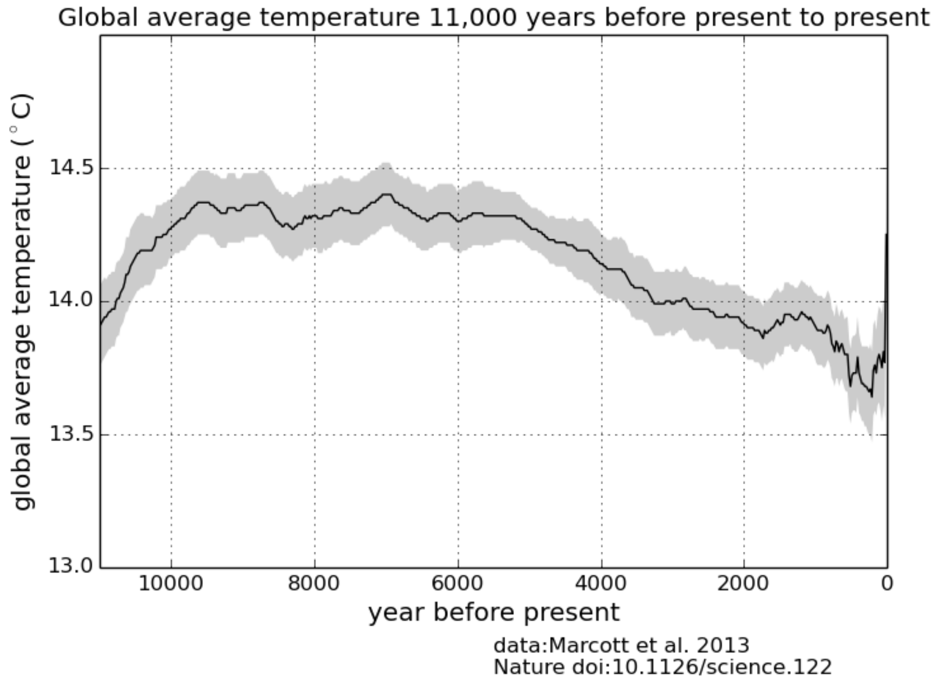
6. Past Climate Change

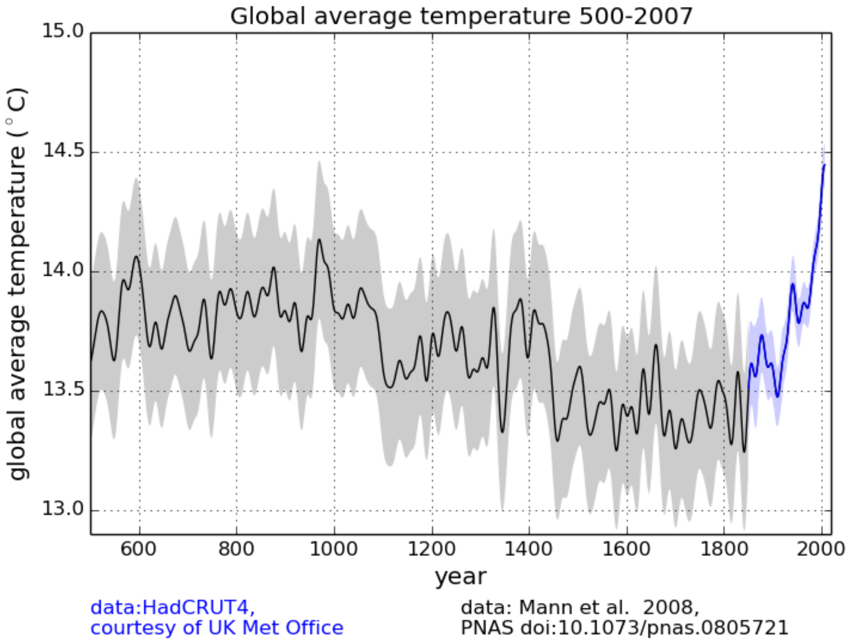
Background Information for Teachers

Past Climate Change

The Earth's climate has always been changing, as some of the factors which control or 'force' it change and the climate system slowly responds.






Global average temperature 500-2007
global average temperature (°C)
year
15.0
14.5
14.0
13.5
13.0
600
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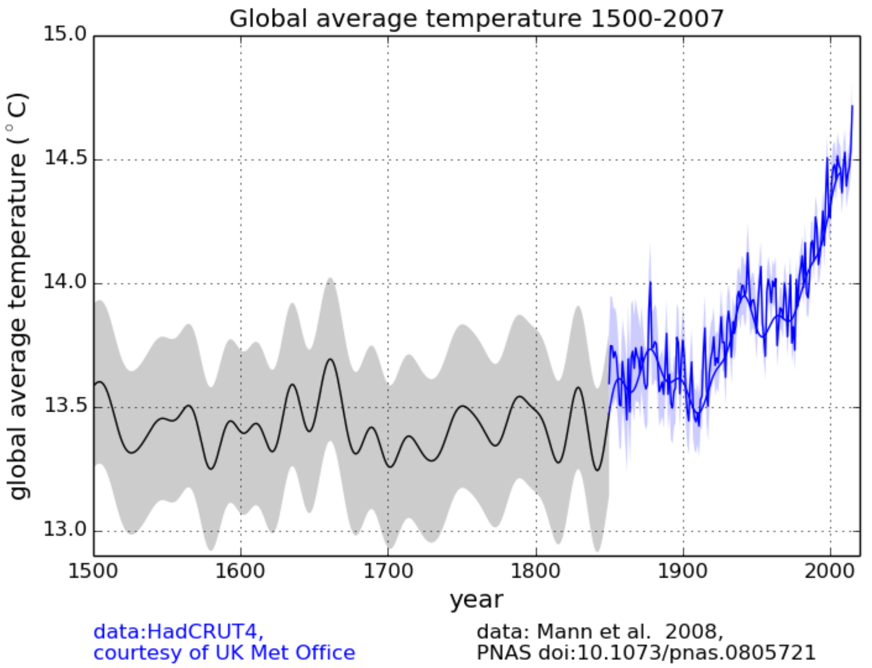
2000
data:HadCRUT4,
courtesy of UK Met Office
data: Mann et al. 2008,
PNAS doi:10.1073/pnas.0805721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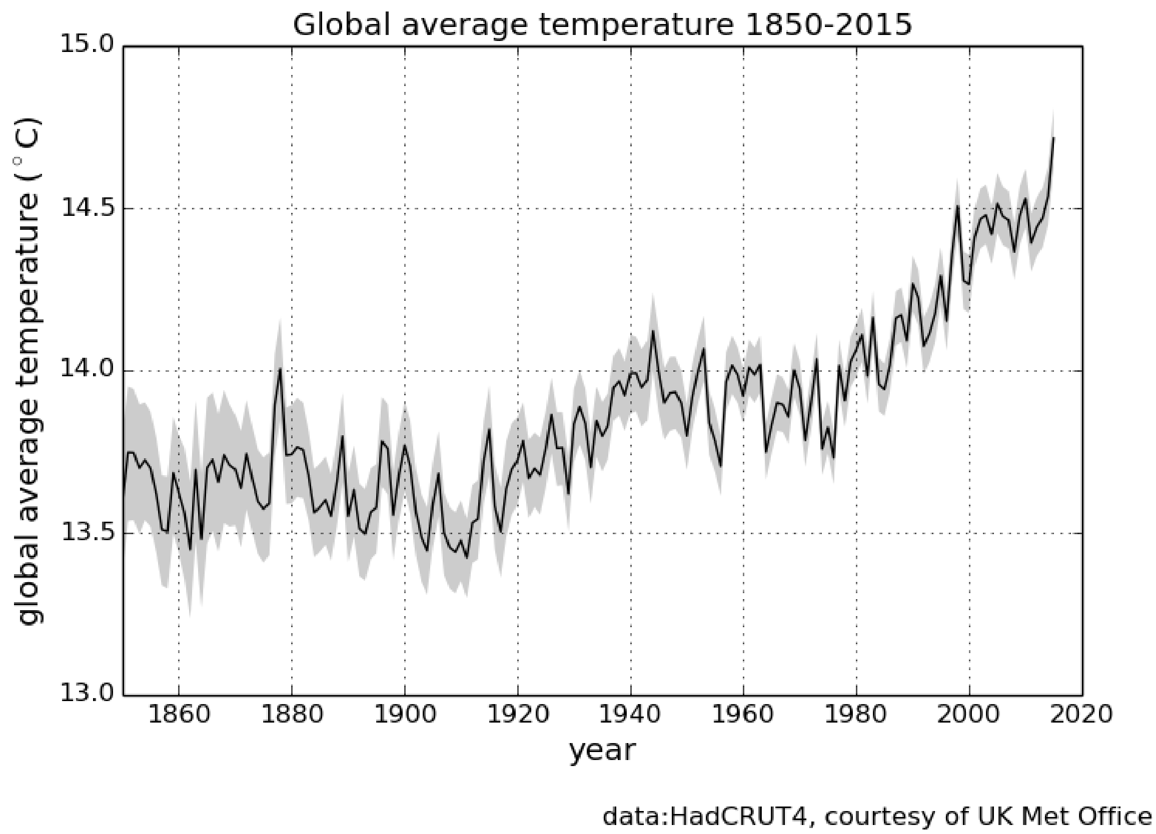


Quaternary climate change in Britain

During the Quaternary Ice Age (the last 2.6 million years of Earth's history) global climate has been fluctuating between cold glacial periods and warmer interglacials, when the climate was similar to the present day. The landscape that we see around us in Britain today has been moulded by these cycles of cold and warm environmental change.

Glacial environments in Britain

During the cold, glacial phases of the Quaternary, a large ice sheet (the British-Irish Ice Sheet) extended across much of the British Isles (Fig. 1). The landforms left behind by the ice sheet allow us to reconstruct the former ice location and flow direction. Such landforms include depositional features such as moraines, and erosional forms such as roches moutonnées.

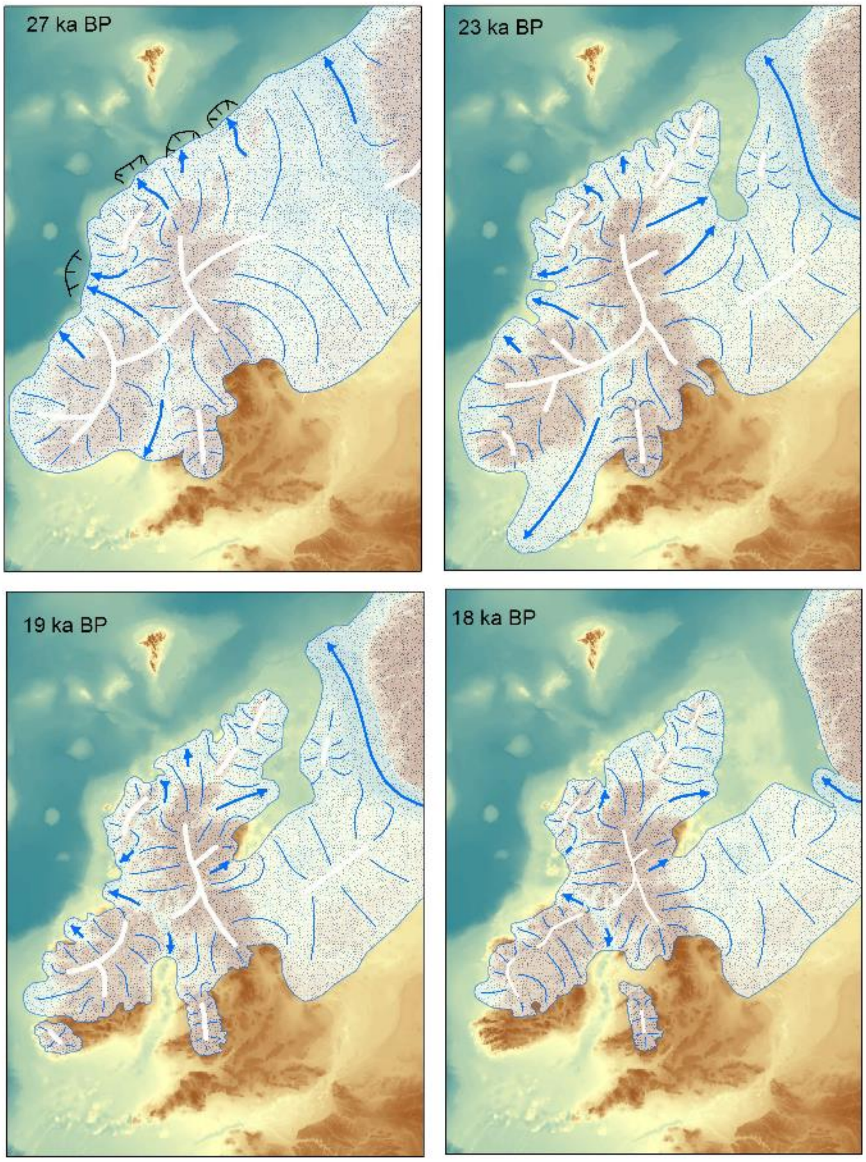
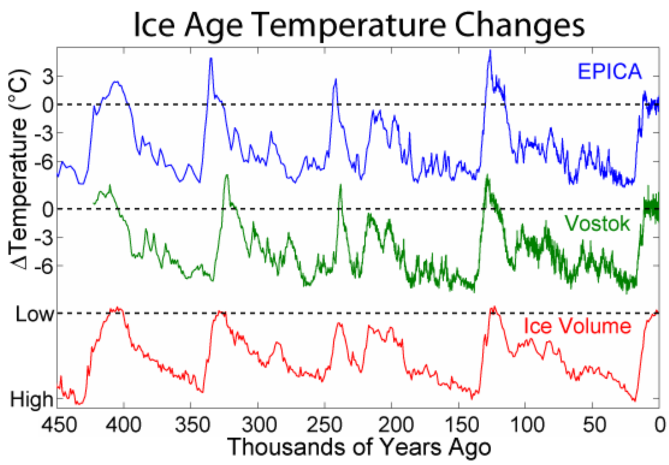


Figure 1 – A reconstruction of the former position and ice flow direction of the British-Irish Ice Sheet at 27,000, 23,000, 19,000, and 18,000 years ago (1ka is 1000 years). Source: BRITICE project, available at: https://www.sheffield.ac.uk/geography/staff/clark_chris/icesheet

Interglacial environments in Britain
In the periods between glacial events, the interglacials, when ice had melted, temperatures in Britain were similar to the present day interglacial, termed the Holocene. In fact, during the last interglacial, around 135,000-70,000 years ago, air temperatures were up to 2°C higher than the present day. In Britain, there is fossil evidence for species of elephant, lion, and hippopotamus frequenting the British landscape at that time. These species are now native only to Asia (elephant) and Africa (elephant, lion, hippopotamus), which indicates the kind of temperatures experienced in the past!

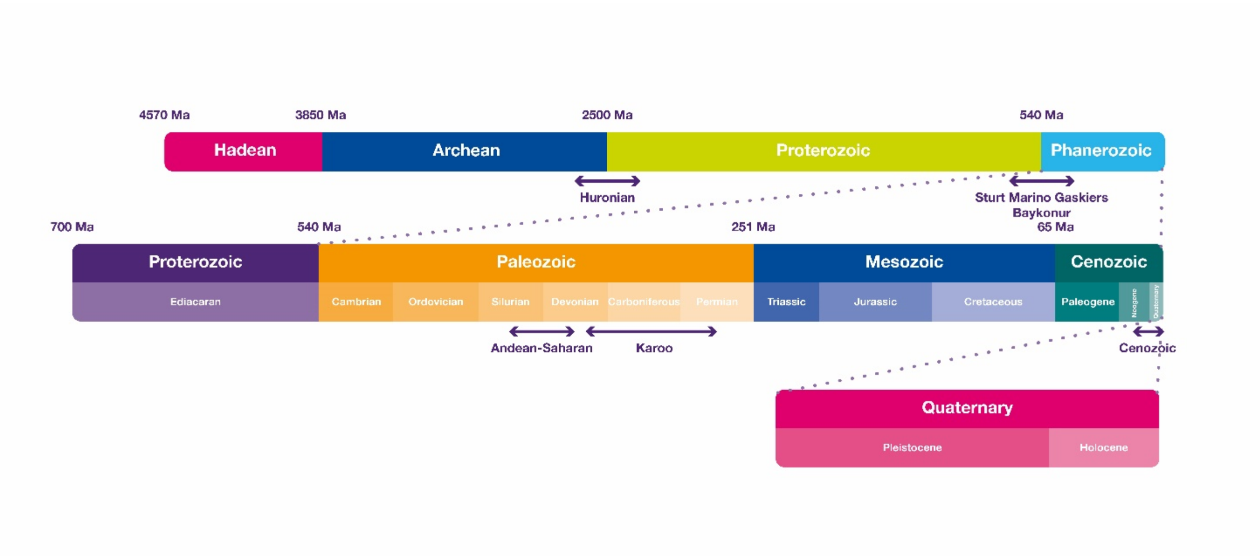
Analysing the environmental conditions of previous glacials and interglacials provides us with important insights into how the British climate might change, under continued anthropogenic global warming.



Air temperature and global ice volume reconstructions for the last 450,000 years from the EPICA and Vostok ice cores, in Antarctica. Robert A Rohde/ CC BY-SA 3.0

Disambiguation: Ice Ages, Glacials and Interglacials

There have been five known Ice Ages in the Earth's history. Currently, we are in the **Quaternary** Ice Age, which started 2.6 million years ago.



During Ice Ages, the environment fluctuates between phases of more severe, cold conditions, known as **Glacials**, and warmer phases known as **Interglacials**. The Earth is currently in an interglacial phase of the Quaternary Ice Age. This particular interglacial is termed the **Holocene**. The last glacial phase of the Quaternary, when large ice sheets spread across much of Europe and North America, ended approximately 11,700 years ago with the start of the **Holocene**. There have been around 30-50 glacial-interglacial cycles in the Quaternary. All Quaternary glacial and interglacial phases except the Holocene are grouped together and known as the **Pleistocene**.

Causes of Change – Milankovitch Cycles and Continental Drift

The Earth's orbit around the Sun changes in 3 ways through time – these are known as the Milankovitch cycles. They do not affect how far away we are from the Sun on average through the year very much, but they do affect which regions of the Earth's surface are facing the Sun at different times of year.

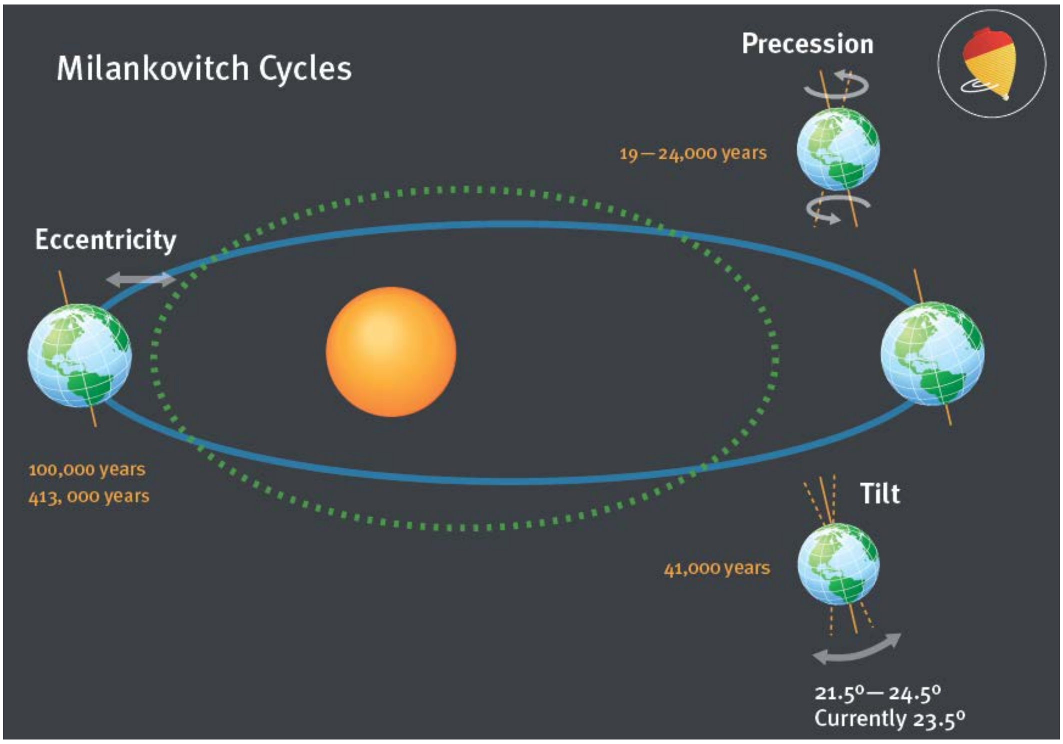


Image source https://www.universetoday.com/39012/milankovitch-cycle/

1) Eccentricity: The combined gravitational pull of the Sun, Saturn, Jupiter and other planets cause the shape of the Earth's orbit to vary from its most elliptical to almost circular. It has a 110,000 year time scale. The Earth is currently closer to the Sun in January than in July, meaning that the seasons are more extreme in the Southern Hemisphere than in the Northern Hemisphere. This means that the Northern Hemisphere receives about 7% less radiation in its summer, and 7% more in its winter, than the Southern in its equivalent seasons. Note that with a more elliptical orbit, the Earth passes closer to the Sun than it ever does on a more circular orbit. This can allow the melting of polar ice in the summer. With a more circular orbit, winter ice can survive the summer and grow in the following winter.
2) Tilt: The tilt or obliquity of the Earth's axis varies over time on a 41,000 year cycle. If the Earth's axis were vertical, we wouldn't have any seasons at all – the same part of the Earth's surface would be facing the Sun throughout the year. The more angled the axis, the more extreme the seasons. Currently, the Earth is tilted at 23.44° from its orbital plane, half way between its maximum and minimum value. The angle is currently decreasing.
3) Precession: The axis also precesses or traces a circle in space on a 26,000 year time period. This is a gyroscopic motion due to the tidal forces exerted by the Sun

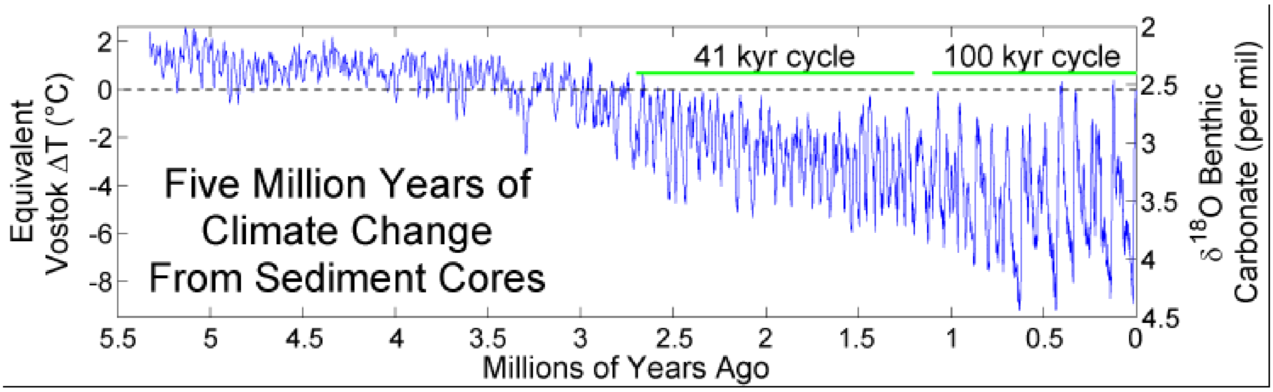
and the Moon on the solid Earth, associated with the fact that the Earth is not a perfect sphere but has an equatorial bulge. It changes which star we see as the North Star – currently it is Polaris, but 13,000 years ago, it would have been Vega.

These processes have an impact on which part of the Earth's surface gets most energy through the year. If you have a look at a globe or a map of the world, you'll see that there is currently far more land in the Northern Hemisphere than in the South. As the way land and vegetation interact with light and heat are very different to the way in which water does, this has an impact on the global climate. As the continents drift, these patterns change.

Coupled with feedback mechanisms (for example, if a polar region receives less sunlight, it cools, allowing more ice to grow, this reflects more light leading to further cooling) these three mechanisms can lead to significant changes in the Earth's climate, including the transition to and from ice ages. Another strong feedback mechanism is associated with the release of greenhouse gases from the ocean as the atmosphere warms, leading to further warming.

The amount of energy arriving in summer at high latitudes determines whether the winter growth of the ice cap will recede or whether the climate will be precipitated into an ice age.

There was a slow cooling of climate over the last 3 million years as polar ice sheets grew partly in response to continental drift. At the Mid-Pleistocene Transition around 1.2 million to 700,000 years ago, the Milankovitch cycles started interacting differently with a shift to a dominant 100,000 year climate signal.



Tropical sea-surface temperature from 3.5 Ma (Million years ago) to present

Tropical sea-surface temperature from 5 Ma (Million years ago) to present. © By Dragons flight (Robert A. Rohde) CC-BY-SA-3.0, via Wikimedia Commons

The planet has gradually cooled since the warmth of the Eocene (around 50 million years ago). This is associated with long-term geological process slowly drawing down carbon dioxide out of the atmosphere. The cooling has not been smooth however, with several transitions identified in the system caused by climate feedbacks (often involving ice). First Antarctica became glaciated around 35 million years ago; then land ice became common in the Northern Hemisphere around 2.7 million years ago.

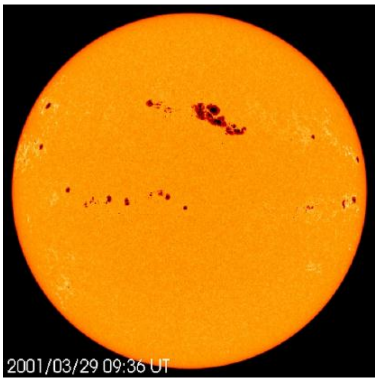
Initially, the amount of ice in the Northern Hemisphere was driven by variations in the obliquity (tilt) of the Earth's orbit (one of the Milankovitch Cycles) - giving roughly 40,000 year-long glacial cycles. Yet as we entered into the past 1 million years, these cycles became visibly longer. Each of the past 8 glacial cycles has lasted around 100,000 years instead of 40,000. The reason behind this shift is unclear and is an area of current research. It is clear that the size of the ice-sheets in the more recent 100,000-year world are larger.

Possible mechanisms are:

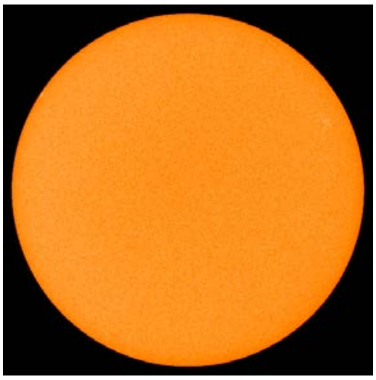
- The ice moves more slowly over land, because all the slippery soil had been worn away and left just bedrock underneath the ice sheets. It therefore builds up higher as less of it gets to the melting zone.
- Unknown changes in the ocean circulation - probably in the Southern Ocean.
- Changes in the dustiness of the atmosphere (associated with long term shift in the vegetation on land) lead to changes in cloudiness and albedo (the amount of the Sun's light reflected back into space without warming the Earth's surface).

Causes of Change – The Sun

29 Mar 2001



16 Jan 2009



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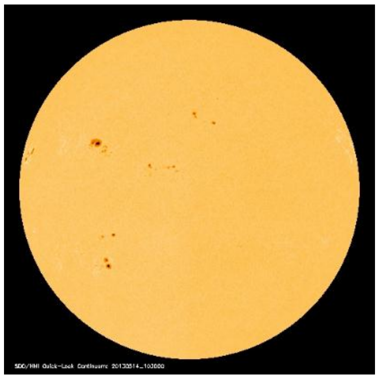
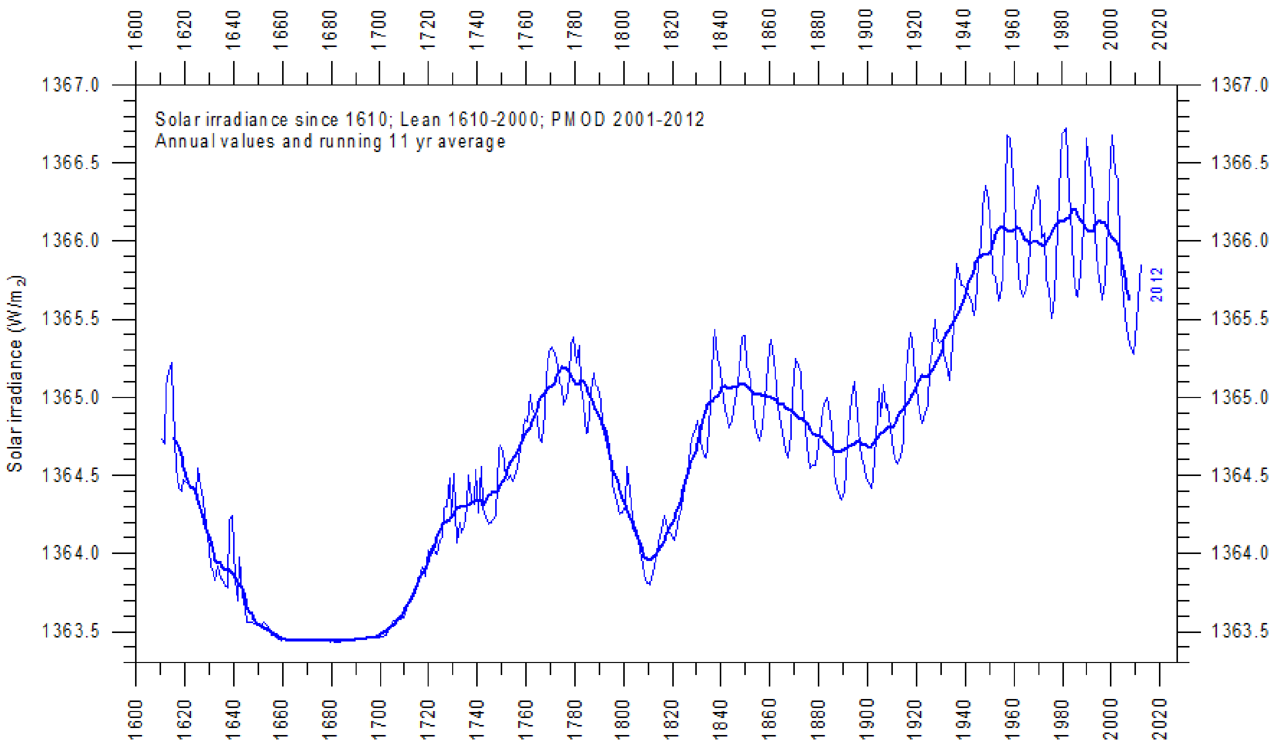


Images from http://sohowww.nascom.nasa.gov/

The more electromagnetic radiation (light, UV light and heat) the Sun emits, the more energy arrives at the top of the atmosphere – the 'solar constant' is higher.

The Sun's output of electromagnetic radiation is linked to the level of sunspot activity. Even though sunspots are darker than the rest of the solar photosphere, the Sun is actually slightly brighter (and the solar constant therefore slightly higher) when there are sunspots, because the Sun emits far more ultraviolet radiation and because of other changes on the surface of the Sun.

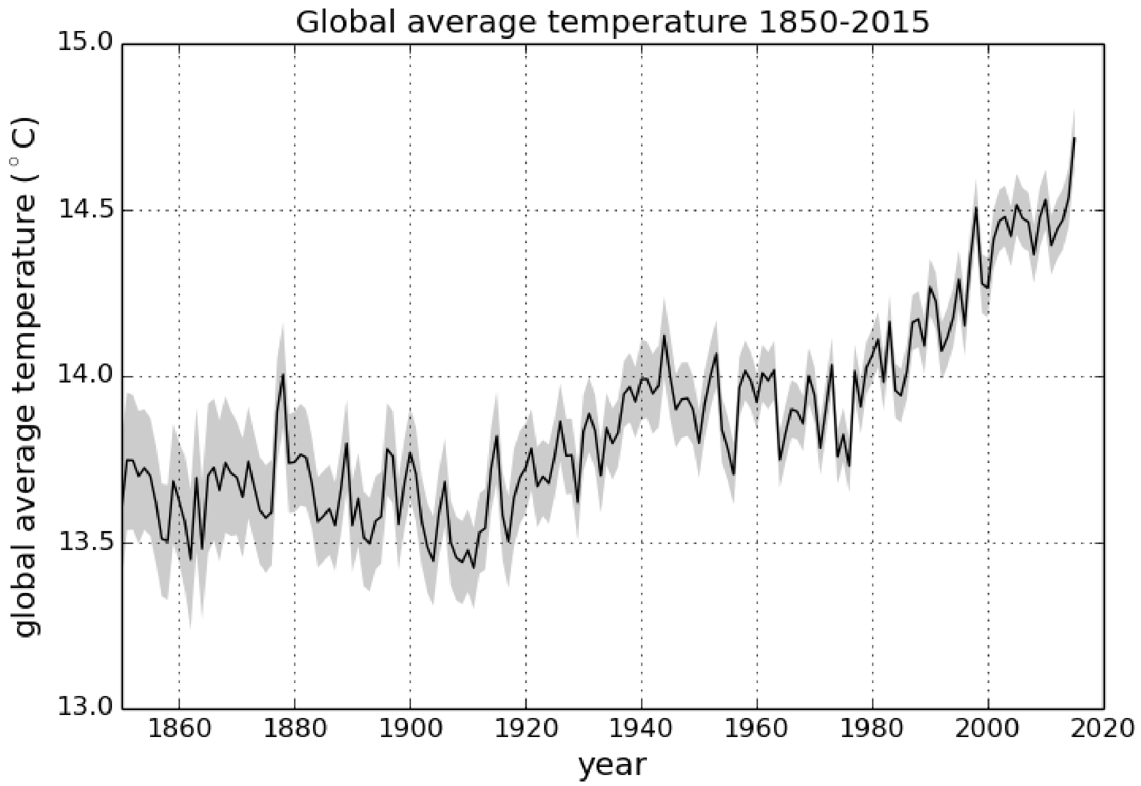
From a global perspective, the processes through which changes in incident solar radiation affect the temperature of the Earth's atmosphere and the climate at the surface, are reasonably well understood. The spectral composition of the radiation is of crucial importance. For example, visible radiation reaches and warms the oceans and land surface, ultraviolet radiation is absorbed by atmospheric oxygen and ozone, while water vapour and carbon dioxide absorb infrared radiation. The production and destruction of some gases, such as stratospheric ozone, also depend on solar ultraviolet radiation. However, the response of climate on regional scales to changes in the composition and intensity of incident solar radiation is more complex. This is an area of active research and, while significant progress has been made, definitive answers require further investigation into effects such as the role of stratospheric ozone, ocean-atmosphere interactions and the role of clouds.



Scientific observations of sunspots began after the invention of the telescope, in 1610, and the approximately 11 year solar cycle, which can be seen clearly in the figure, was identified in 1843. Changes in the solar constant through an 11-year cycle are typically less than 0.1% (note the y axis scale on the graph), with an estimated global temperature response of less than 0.03ºC. Nevertheless, some correlation has been noted with droughts, temperature, ozone etc. suggesting that there may be some feedback mechanisms.

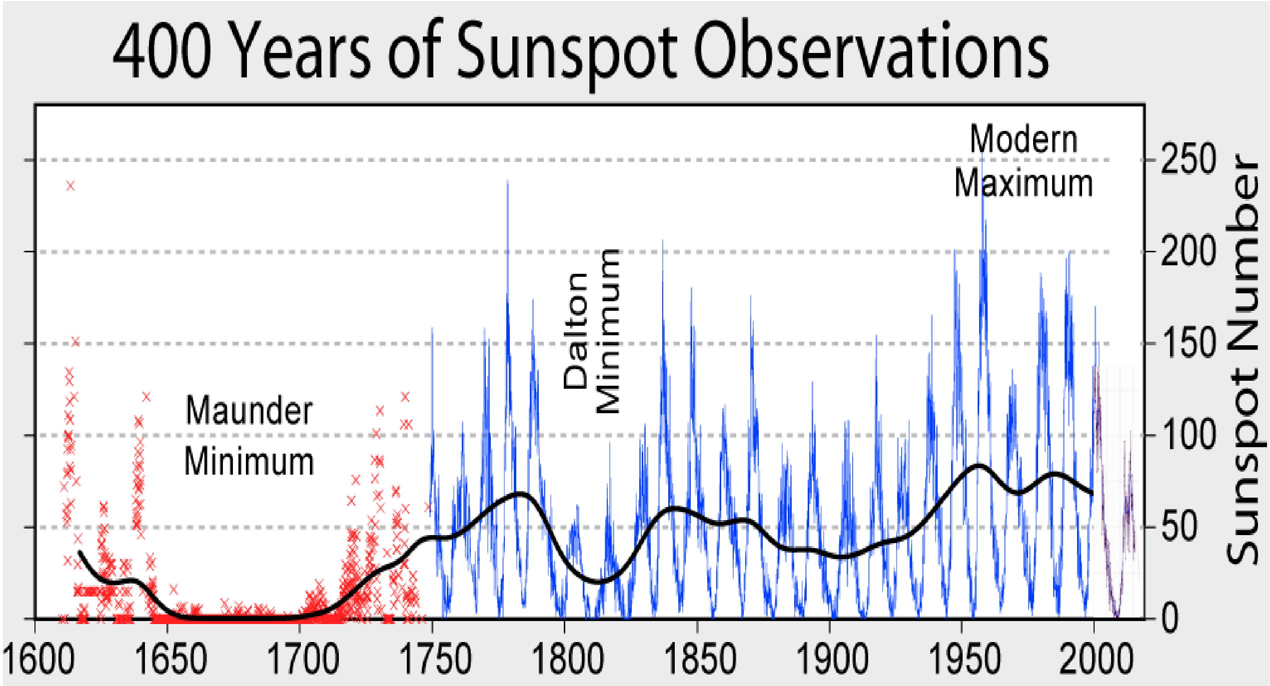
From 1645-1710 there were virtually no sun-spots; a period known as the Maunder Minimum.

There has been no net increase in solar brightness since the 1970s, and the Sun is currently in decline. Predictions for the next century suggest that there may continue to be a slight reduction in sunspot numbers.



data:HadCRUT4, courtesy of UK Met Office

The warming seen from 1900-1950 was due to the combination of already increasing greenhouse gases, an increase in solar activity and a lack of volcanic activity.
The Sun may have introduced an overall global warming (disregarding 11-year cycle modulation) of approximately 0.07 °C before about 1960 but has had little effect since.
The cooling in the 50s and 60s was due to aerosols – other atmospheric pollutants we were emitting which were making it cloudier, reflecting the Sun's light. Clean air acts, designed to reduce acid rain and improve air quality, have started to reduce these, at least in Europe.
Subsequent warming has been seen as the concentration of greenhouse gases in the atmosphere increases rapidly with their related feedbacks.



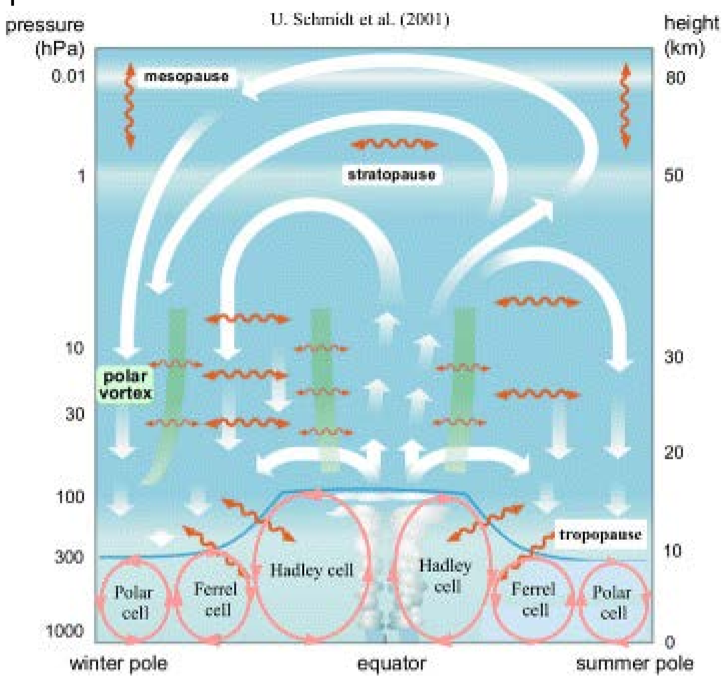
Robert A. Rohde/ CC BY-SA 3.0

The Maunder Minimum in solar activity is connected with the Little Ice Age – a period of general cooling, at least in the Northern Hemisphere, although this has also been linked to major volcanic eruptions in the 13th century onwards, and the European colonization of the Americas, coupled with ice feedbacks.
The Dalton Minimum may have contributed to the bad weather, and related failures of harvests and general distress, at the start of the 19th Century.

Causes of Change – Volcanoes

Huge explosive volcanic eruptions in the Tropics, energetic enough to push sulphur gases up into the relatively stable stratosphere where they condense into aerosol (small particles), can have a cooling effect on climate by increasing the albedo of the atmosphere. More of the Sun's light is reflected by the aerosols before it reaches the ground. The eruption of Pinatubo in 1992 resulted in a global cooling of up to half a degree for a couple of years. Other recent energetic eruptions include El Chichon (1982) and Agung (1963) which were preceded by half a century of little volcanic activity. The combined eruptions of La Soufrière (1812), Mayon (1814) and Tambora (1815) had catastrophic global effects, leading to a 'year with no summer' in 1816.
In the troposphere, the temperature mainly falls with height. Air rising through the troposphere cools (at the adiabatic lapse rate) and as it cools, can be either warmer or colder than the air around it.
On the other hand, in the stratosphere, the temperature increases with height. This is because the ozone in the ozone layer absorbs the Sun's UV and reemits the energy as heat, warming the stratosphere. This means that any air trying to rise from the troposphere, cooling as it rises, will always be colder than the surrounding air, and will sink back to the troposphere.

You can see from the shape of the cumulonimbus cloud at the top, that air rising in the unstable troposphere reaches the top of the troposphere, the tropopause, and then can't rise into the stratosphere, so it has to spread out sideways.
Only very explosive volcanoes can blast material past the tropopause.
If the volcanic material remains in the troposphere, it is fairly rapidly removed – e.g. by rain. If it can get up into the stratosphere, it has an impact for much longer.
Eruptions that are mainly restricted to the troposphere are much less likely to alter climate, for two main reasons:
Firstly, the SO_2 emitted by the volcano will not all be oxidised to sulphuric acid aerosol, as gas deposition processes operate on similar timescales to oxidation.
Secondly, the aerosol generated will be efficiently removed by deposition processes (e.g. rain), and it will have a tropospheric lifetime of only days to weeks, compared with months to years in the stratosphere.
If material makes it into the stratosphere, it gets caught up in the Brewer-Dobson circulation
Major eruptions in lower latitudes are more climatically effective as the aerosol is capable of reaching the higher latitudes of both hemispheres, because of the direction of the atmospheric circulation. Material from major eruptions in the middle-to-high latitudes of each hemisphere tends to remain poleward of the eruption latitude. Major Icelandic or Alaskan/Aleutian/Kamchatkan eruptions, therefore, only influence the higher latitudes of the Northern Hemisphere.



Brewer Dobson Circulation (adapted from Bönisch et al, 2011)

To affect global climate, a volcano should be;
Explosive – for material to reach the stratosphere,
Low latitude – for material to be spread through both hemispheres.
Cooling is most pronounced over **land** regions because the thermal inertia is much smaller than over the oceans i.e. it's quicker for them to heat up or cool down. As there is

less land in the Southern Hemisphere, the cooling there is less than in the Northern hemisphere but lasts longer.

The effects in the Northern Hemisphere are greatest in the **summer** season because, then, the Sun's radiation levels are at their maximum (and so increasing the reflectivity of the atmosphere will have the biggest effect). The crucial factor in determining the climate impact is not necessarily the magnitude of the eruption but is thought to be the quantity of sulphur dioxide (SO_2) injected into the stratosphere.

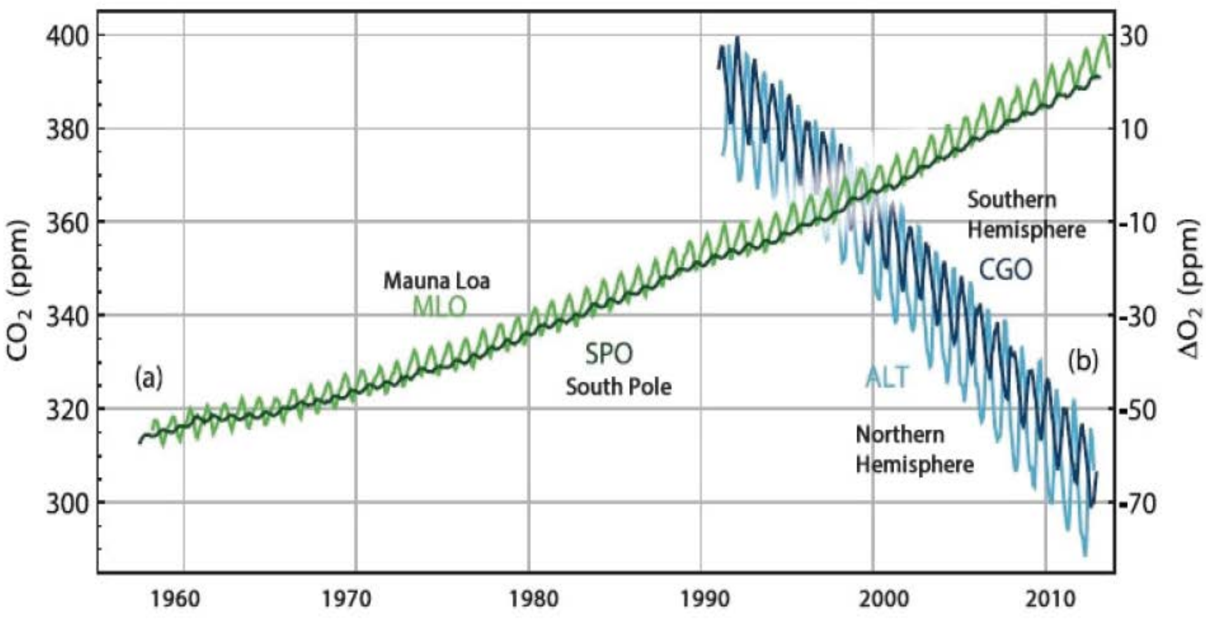
Ash is removed from the atmosphere far faster than SO_2.

A more dramatic change in albedo is associated with the 'snowball Earth' hypothesis. It has been suggested that during the Proterozoic (850-630 million years ago) the positive albedo feedback associated with ice accumulation (as the Earth cools, more light coloured ice forms, which reflects more of the sun's light, leading to further cooling) led to ice covering the whole Earth. In this scenario, volcanoes and the huge amounts of greenhouse gases they can emit, would be necessary to break out of the ice-climate feedback.

Super volcanoes are any volcano capable of producing a volcanic eruption with an ejecta mass greater than 10^{15} kg. For example;

- Toba, Sumatra (74,000 years ago), preceded a major glaciation.
- Yellowstone (640,000 years ago), led to 5°C global cooling.

Causes of Change – Atmospheric Composition

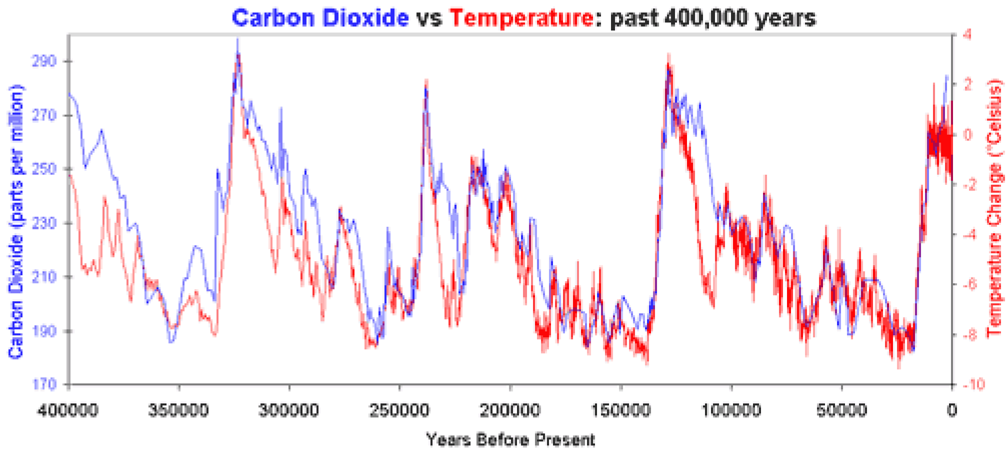


Concentrations of carbon dioxide and oxygen in the atmosphere. Atmospheric concentration of a) carbon dioxide in parts per million by volume from Mauna Loa (MLO, light green) in the Northern Hemisphere and the South Pole (SPO, dark green) and of b) changes in the atmospheric concentration of O_2 from the northern hemisphere (ALT, light blue) and the southern hemisphere (CGO, dark blue).

This will be covered in detail in chapter 12.

Temperature and Carbon Dioxide – Chicken or Egg?

Data from Antarctic ice, such as the Vostok ice core, show that carbon dioxide levels in the atmosphere and atmospheric temperatures fluctuate roughly together:



Vostok Ice Core records of temperature and atmospheric CO_2 concentration
Source https://skepticalscience.com/co2-lags-temperature.htm

The initial changes in temperature during interglacial periods are explained by the Milankovitch cycles. As ocean temperatures start to rise, the solubility of carbon dioxide in water decreases and so the oceans release CO_2 into the atmosphere. In turn, this release amplifies the warming trend, leading to yet more CO_2 being released. This positive feedback is necessary to trigger the shifts between glacials and interglacials as the effect of the Milankovitch cycles alone is too weak. Additional positive feedbacks which play an important role in this process include other greenhouse gases, and changes in ice and vegetation patterns. The increase in carbon dioxide lags behind the increase in temperatures.

In much more recent times, changes in carbon dioxide concentrations in the atmosphere have preceded temperature increases.

Find out more: http://www.realclimate.org/index.php/archives/2007/04/the-lag-between-temp-and-co2/ and https://skepticalscience.com/co2-lags-temperature.htm

Anthropogenic Climate Change v. Natural Climate Change

If there had been no anthropogenic impact on greenhouse gas concentrations in the atmosphere, and the natural carbon dioxide levels had got down to 240ppm, then the

Earth would be cooling to a glacial phase within the next 1500 years. Otherwise, if greenhouse gas levels didn't naturally get down that far, the next glacial would be in 50,000 years.

However, with greenhouse gas levels as they currently are, without any further emissions, the next glacial won't come for around 100,000 years.

What is the Anthropocene?

Humans are significantly altering the planet – physically, chemically and biologically. They are now a geological force that can control evolution of climate. Earth's history is divided up into sections – partly according to forces at play, each section has a distinct marker. "Anthropocene" is the name of a proposed new section where Humans dominate.

When should the start of Anthropocene be?

Some proposed markers are:

Early Anthropocene	3070 BCE	Farming and civilisation
Orbis	1610 CE	Colonialism and global trade
Industrial Revolution	1712 CE	Coal and Industrialisation
Great Acceleration	1964 CE	Nuclear bombs and consumerism

Sources of Information

Did the European conquest of the Americas contribute to the Little Ice Age?
https://www.metlink.org/wp-content/uploads/2020/05/GA-TG-Sum-2019_Knight.pdf

Current sun spots: https://sohowww.nascom.nasa.gov/sunspots/

Current volcanic activity: https://volcano.si.edu/gvp_currenteruptions.cfm